Electromagnetic response functions in proton-proton scattering

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Chapter 1

Introduction

The strong force, according to our present understanding, is described by the theory of quantum chromodynamics (QCD). However, much below the region of energies at which the interaction of nucleon constituents starts to reveal its properties, the strong force was (and still is) investigated by means of a phenomenological nucleon-nucleon (NN) interaction and by probing the nuclei via different probes. Due to the non-perturbative nature of QCD at low energies, which are characteristic for nuclear physics[1], we still use until now so-called effective degrees of freedom in models describing the NN interaction. The effective[2] models or potentials [Sto93, Sto94, Wir95, Mac96], which are presently regarded as the state-of-the-art (NN) potential calculations, incorporate most or at least the most important, phenomena related to our understanding of the NN interaction. Our interest in the NN potentials is governed by our wish to interpret or predict the NN scattering data as well as possible. Another long standing desire is to use such a potential as a building block to explain even highly complex systems such as nuclei.

In contrast to the effective models which are based on the field theory approach, the phenomenological models utilize physically observable quantities in the development of the potential models. Although not as sophisticated as models based on the field theory approach, the phenomenological models serve as useful alternative, especially if tuned

[1]Actually, it is hard to draw a clear line where the nuclear region stops and where particle physics begins.

[2]The models are called effective because they use effective degrees of freedom to describe observable phenomena.

for a particular purpose. Concerning the subject of this work, the difference between these two approaches is that the off-shell behaviour is well-defined in the field-theory approach and approximated in a plausible way in the phenomenological approach, where the reaction amplitude is evaluated from the on-shell state.

The permanent development has led us to the present situation in which all effective potentials can describe elastic NN scattering data equally well (with $\chi^2 \approx 1$ per datum). The elastic cross sections as well as analyzing powers for the NN scattering are accurately known today, and the models are in a good agreement with the experimental data. This, however, is not enough to explain the interaction of nucleons in nuclei where they are bound and their effective mass is different than for the free nucleons. The effect is introduced in the NN interaction model as the off-the-mass-shell effect. In this work the inelastic NN scattering is used to test descriptions of the effective nucleon mass.

1.1 Proton-proton (virtual) bremsstrahlung

The simplest[3] way to address the issue of the off-shell nucleon behaviour is to look at the bremsstrahlung production in the inelastic NN scattering. The original German term *bremsstrahlung* or breaking radiation designates an electromagnetic radiation that originates from the decelerated motion of a charged particle. The photon produced in the bremsstrahlung process is used as a probe for the off-the-mass-shell nucleon in the NN interaction, or the other way around, the off-shellness of the nucleon results in producing the photon. Fig. 1.1 shows the Feynman diagrams representing the bremsstrahlung production in the reaction $N + N \rightarrow N + N + \gamma$, where a one boson exchange potential (OBEP) is used to describe the NN interaction. The coupling between photon and nucleon is a quantum electrodynamics (QED) process and the vertex is evaluated in a so-called vector-meson dominance (VMD) model which assumes that the photon couples to the nucleon through a vector boson. As discussed further in this section, the modification of the vertex due to the off-shell nucleon is regarded negligible.

[3]Other inelastic processes are also used to probe the off-shell nucleon behaviour, e.g. $pp\pi^0$, but using the photon has an advantage that the photon couples to the nucleon via the (weak) electromagnetic interaction. Pions and other mesons can interact with the nucleon via the strong force which requires complicated final-state interactions to be taken into account.

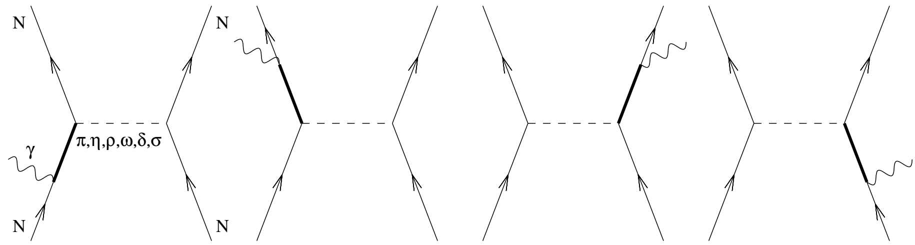

Figure 1.1: The leading order diagrams for the the $N + N \rightarrow N + N + \gamma$ process; the emitted photon is coupled to the external legs. In the left-most diagram exchanged mesons characteristic for the NN interaction are indicated.

So far we were discussing the NN interaction in general, but there are a few reasons why the *pp* scattering is from the experimental point of view preferred to the *pn* scattering. First of all, the bremsstrahlung production is a very weak process in comparison to the elastic scattering. To enhance the statistics a high luminosity is required, which is partially realized through a high-density target. This consequently allows one to achieve a better signal to background ratio by applying well devised trigger conditions. High quality and high intensity polarized-proton[4] beams are today commonly available making the *pp* scattering a better choice. Furthermore the detection of protons is considerably simpler than the detection of neutrons.

From the physics point of view, the underlying model for the *pp* system is simpler than for *pn* because only the neutral meson exchange currents (MEC) are used in the OBEP and the photon is not coupled to the neutral mesons. Also the E1 electric dipole radiation is forbidden for the *pp* system.

In recent years, a substantial effort, experimental [Hui02, Sha04] as well as theoretical [Kor95, Kor96, Mar97a, Mar97b], has been put to address the bremsstrahlung production below the pion production threshold. The cross sections and the analyzing powers obtained with an unprecedented statistical accuracy by [Hui99] and [Sha04], have triggered recent theoretical developments [Cos02, Sch02, Cos03]. Noticeable is that the experimentally obtained accuracy allows for a high

[4]The polarized-proton beams are used to study the spin-dependence of the *pn* interaction.

sensitivity to the predictions of the different models.

In addition to the real bremsstrahlung ($pp\gamma$ final state), in which the real photon is produced, one can study the virtual bremsstrahlung (ppe^+e^-), where the electron-positron (dilepton) pair (e^+e^-) is produced. The production of the dilepton pair, which is illustrated in Fig. 1.2, is associated with the production of a virtual photon $\gamma^* \longrightarrow e^+e^-$ in the time-like region of 4-dimensional space time, where the invariant momentum transfer squared $q^2 > 0$. Compared to the real

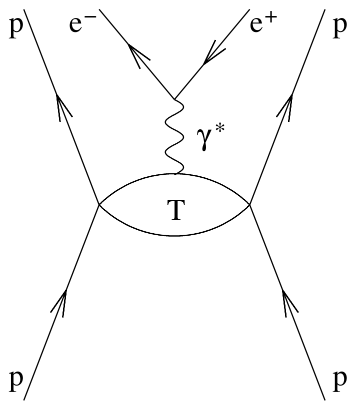

Figure 1.2: The general Feynman diagram illustrating the virtual bremsstrahlung production. Here T designates the pp scattering T-matrix.

photon, the virtual photon has invariant mass $M_\gamma^2 = q^2 > 0$. Therefore, it exhibits a transverse and a longitudinal polarization. A particularly interesting property for this work is that the angular distribution of the two leptons enables a decomposition of the cross section into six different components, related to the polarization of the virtual photon. This can be used to enhance the sensitivity to the specific amplitudes of the reaction mechanism. One should note that the virtual bremsstrahlung probes the nucleon electromagnetic form factor in the time-like region. In addition, the massive photon causes a modification in the VMD model of the electromagnetic coupling. However, for the energies of this experiment with the virtual photon mass $M_\gamma < 92$ MeV, the effect is estimated to be less than 2% in the cross section [Mes99], and it is consequently disregarded.

In comparison to real bremsstrahlung, the cross section is even smaller by a factor $\alpha = 1/137$ and a higher luminosity is required.

In the pilot experiment performed at the KVI by Messchendorp *et al.* [Mes00], a first insight into the experimental study of the virtual bremsstrahlung below the pion production threshold was gained. The cross sections were obtained and the feasibility of a more detailed investigation was established. Overall, a valuable basis was created for the experiment presented in this thesis. As a major improvement in comparison to the pilot experiment, the experimental setup was upgraded by employing the Plastic Ball detector for the lepton detection. This has resulted in much better coverage of the dilepton phase-space.

The pilot experiment has also triggered the development of theoretical models describing the dilepton production. These models are usually developed as an extension of the real bremsstrahlung models. The model based on the low-energy theorem (LET) [Low58] was developed by Korchin and Scholten [Kor95] and subsequently extended [Kor96] following the developments of the models of the real bremsstrahlung production [Lio93]. The general characteristic of the models based on the LET approximation is that the reaction amplitude is derived in terms of the on-shell (elastic scattering) T-matrix. In this work we will use two different approaches to the LET resulting in two different LET models [Kor96]. Since we are using the Monte Carlo (MC) technique to perform a phase-space integration, the advantage of the LET models is that the calculation is fast and easy to evaluate.

Another type of calculation is the microscopic model developed by Martinus *et al.* [Mar98]. The model is based on the fully relativistic OBE Fleischer-Tjon potential [Fle74]. In this calculation a scattering T-matrix contains the off-shell dynamics of the intermediate protons. The photon coupling is made to the external and the rescattering diagrams. In addition, the meson exchange and the Δ-isobar contributions are added pertubatively. The calculation enables the investigation of contributions from all above mentioned mechanisms in an elegant way, but, due to its high complexity, the evaluation of the calculation is rather slow in comparison to the LET calculation, and, consequently, not very suitable to be used in a MC approach. Therefore, it was not employed in our work.

In comparison to the pilot experiment, where about 600 background-free events were obtained, the analysis of the experiment has left us with about 3500 background-free ppe^+e^- events from which the cross sections were calculated. The main objective of this work was to extract different response functions from the decomposition of the measured cross section. An attempt for the extraction was already made in the pilot experiment. In this thesis we present the results and discuss the problems that one encounters in the study of virtual bremsstrahlung production below the pion threshold.

Outline of this work

In chapter 2 the kinematics and dynamics of the ppe^+e^- reaction are introduced. The differences of the two theoretical models used to describe our data are outlined. Chapter 3 is concerned with the Monte Carlo approach/technique of the phase-space integration that was used to compare results and to obtain predictions for the LET model calculations. We also give a detailed description of the procedure for the extraction of response functions. The experimental apparatus is explained in chapter 4. A setup comprising two independent detector systems was employed in our experiment. The data analysis is explained in chapter 5. Finally, the results are presented and discussed in chapter 6.